FAA/EUROCONTROL COOPERATIVE R&D

Action Plan 16: Common Trajectory Prediction Capability

Validation Data Methodology

EXECUTIVE SUMMARY

Unless broad categories of improvements are made, most air service providers view the future of civil air transport as increasing in demand faster than capacity, making it increasingly difficult to maintain yet alone improve the current levels of safety and efficiency. One illustration of improvement envisioned is the implementation of flight data processing systems and the complex decision support tools (DST) that can assist the air traffic controllers and other decision makers within the air traffic management (ATM) system. Thus, advanced and reliable DSTs are the functional enablers of future ATM concepts. They provide support such as flight data, metering, or conflict prediction functions. Their capabilities are directly linked to the performance of the sustaining trajectory predictor (TP) that is responsible for predicting the anticipated future path of the aircraft. As a result, the accuracy of the TP is critical to the success of these DST functions.

To help meet this future challenge, an international team of researchers and practitioners has been formed under the initiative of the FAA-Eurocontrol Action Plan 16 (Common Trajectory Predictor Capabilities). This team is creating a common methodology and set of resources for the validation and improvement of trajectory prediction capabilities. A generic TP structure has been constructed and decomposed into individual services. This TP structure allows for the description of specific elements of the TP that can be validated during different stages of the process. The team is in the process of developing a common TP validation strategy, which can be universally applied to one or more elements of this TP structure. The TP validation strategy will consist of a common set of trajectory data, methodologies, and error metrics. In order to provide a catalyst for discussion on the development of a common TP validation strategy, this paper presents a TP validation strategy previously proposed by members of the team. Yet to be implemented in its entirety, the opportunity exists to modify this strategy and incorporate methodologies and experiences of the TP validation community. The goal is to develop a TP validation strategy that is effective, efficient, and accepted by all.

It is recommended that the community participate in the development of a common TP validation strategy, and contribute to the construction and use of the common validation trajectory database. It is requested that the community (1) provide feedback on this methodology paper, (2) share specific TP validation methodologies and experiences at the upcoming Technical Interchange Meeting in November 2004, and (3) contribute trajectory data to the validation database.

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VALIDATION DATA METHODOLOGY

1. Introduction

The typical view of most air service providers in both the United States and Europe is that air traffic will continue to grow. Most believe this growth will out pace the capacity limits of the aviation system, resulting in congestion and further inefficiency. To prevent this, broad categories of advances in ground and airborne automation are envisioned. One of the automation advances considered universally is the decision support tool (DST). These tools serve to lower the complexity of airspace problems faced by the current human decision makers operating the system. These tools have many purposes. They include tools that serve to predict future conflicts between aircraft both for ground based controllers or airborne pilots, allowing more strategic separation management of aircraft. DSTs can include traffic management tools that forecast where and when traffic workload would stress the system, allowing air traffic supervisors to make more efficient adjustments to either avoid the condition or alter staff and/or airspace accordingly. These can also include air traffic metering tools to efficiently sequence aircraft into arrival flows, maximizing the capacity of the system. A common thread in all these DSTs is the accurate and timely modeling of the aircraft's current state and anticipated future path. This function is referred to as the trajectory predictor process or TP. The trajectory is the actual or future four-dimensional path of the aircraft. Accuracy of a trajectory modeler can be measured by performing post flight comparisons between predicted and observed aircraft trajectories. Since the trajectory is the fundamental input that sustains the DST's capabilities and functions, the accuracy of the TP has a direct impact on the DST's overall performance and usability.

To ensure the DST has the proper TP, a validation task should be performed to check that the TP conforms to specified accuracy requirements. The verification and validation process can then drive the TP performance toward a targeted level. The objective of this paper is to provide a catalyst for the development of a common TP validation strategy that supports the improvement of a TP. The TP validation strategy proposed is a framework in which the methodologies and experiences of the TP community can be incorporated. The goal is develop a TP validation strategy that is effective, efficient, and accepted by all.

2. Overview of the Proposed Improvement Process

The proposed improvement process is accomplished by establishing a TP validation strategy and an associated database of generic TP validation data, collected from a multitude of sources. This includes derived data, such as aircraft performance model data, flight management system recordings, or simulation data, which can exercise only parts of the TP but available at high levels of accuracy. This also includes operational data, such as aircraft flight data recordings from experimental flights tests to air traffic control system recordings. This air traffic data contains a broader set of operational conditions but may lack the detail provided in the derived data sets. By utilizing all these data sources in a layered approach as first presented in [1], the TP is dissected into its inner and outer control loops and tested with the various data sources. The inner TP processes are validated first with the derived data sets. As these inner processes are validated and errors are identified, resources can be focused to the appropriate unit and improvements made. Once these inner processes are improved, the broader operational data sets can be implemented to test the outer processes and re-test the inner processes. Further description of these control loops will be provided in subsequent sections of the paper. The fundamental characteristic of this approach is the process is iterative and systematic. The approach will serve to "bake down" the errors in an iterative process, increase confidence at each step, and lead to an improved TP that more closely meets the original DST requirements.

For any single air traffic provider developing a specific DST, the cost of assembling this relatively large data collection could be prohibitive. However, the cost is significantly less by leveraging among many air traffic providers and building a community TP validation database. Under Action Plan 16 of the Eurocontrol/FAA R&D Committee and the CARE/TP Action, validation data is being collected from the FAA, NASA, Eurocontrol, and various European air traffic service providers and stored on Eurocontrol's OneSky Internet file server[1].

By also collaborating and agreeing upon a common set of metrics, the TP's inner and outer control loops can be cross-compared among developers. This would encourage developers to leverage ideas and approaches for improvement as well as the data used to identify them.

The subsequent Section 3 will first describe a generic TP and its context within the Air Traffic Management (ATM) system. Next, in Section 4, the paper will discuss more detail on the validation data types and application of this data to the TP improvement process. Section 5 will present a description of common metrics, and the body of the paper concludes in Section 6 with a request for TP developer participation with specific recommendations.

3. Trajectory Predictor

An aircraft trajectory prediction refers to the development of an estimate of the future positions of a flight given the aircraft initial conditions, a notional path to be followed by the aircraft, environmental information, and aircraft-specific data (such as an aircraft performance model).

Several different approaches exist for aircraft trajectory prediction with differing levels of fidelity and data requirements. However, in almost all cases the following categories of data are required:

- *Initial condition*. This refers to the aircraft state and time at the start of the trajectory calculation. The aircraft state vector will include a greater number of elements in the case of a higher-order model. For example, a full motion simulator would require instantaneous bank angle, whereas a point-mass model would not.
- *Intent information*. This describes the notional path and/or constraints the aircraft will follow in the future. This may be a sequence of control instructions for the aircraft (full control settings schedule), a flight plan, or a simple projection of the state vector (fixed heading and speed). Intent information can also include the effect of operational procedures (e.g., how a climb is executed by the flight crew, altitude restrictions, etc.)
- *Environmental information*. This refers to external elements that will affect the aircraft behavior, such as winds and temperature aloft.
- *Aircraft-specific information*. This includes the aircraft performance model and flight-specific data such as weight.

Figure 1 illustrates an example of the trajectory prediction process as applied to a commercial flight already en route. This example refers to a generic trajectory prediction process; some trajectory predictors would require more, different or less information. Increased sophistication

[1] See http://www.eurocontrol.int/oneskyteams.html for registration details.

in predictors can also lead to intent inferencing, in-flight parameter estimation or trajectory error monitoring and recalibration.

This trajectory predictor will have access to the flight plan containing the flight number (e.g., AAA123), the aircraft type (B-757-200), the filed cruise speed (true airspeed of 450 knots), the desired cruise altitude (31,000 feet), and the route of flight (departure from XXX, now heading to ABC, then DEF, finally to XYZ via the BUC 7 STAR). Furthermore, the trajectory predictor will have an estimate of the initial condition (the present aircraft position, speed and heading). Prior to conducting trajectory prediction, the flight plan route, expressed as named points, will be converted to a series of geographical points (e.g., latitude and longitude). This process is known as ***route conversion*** [2].

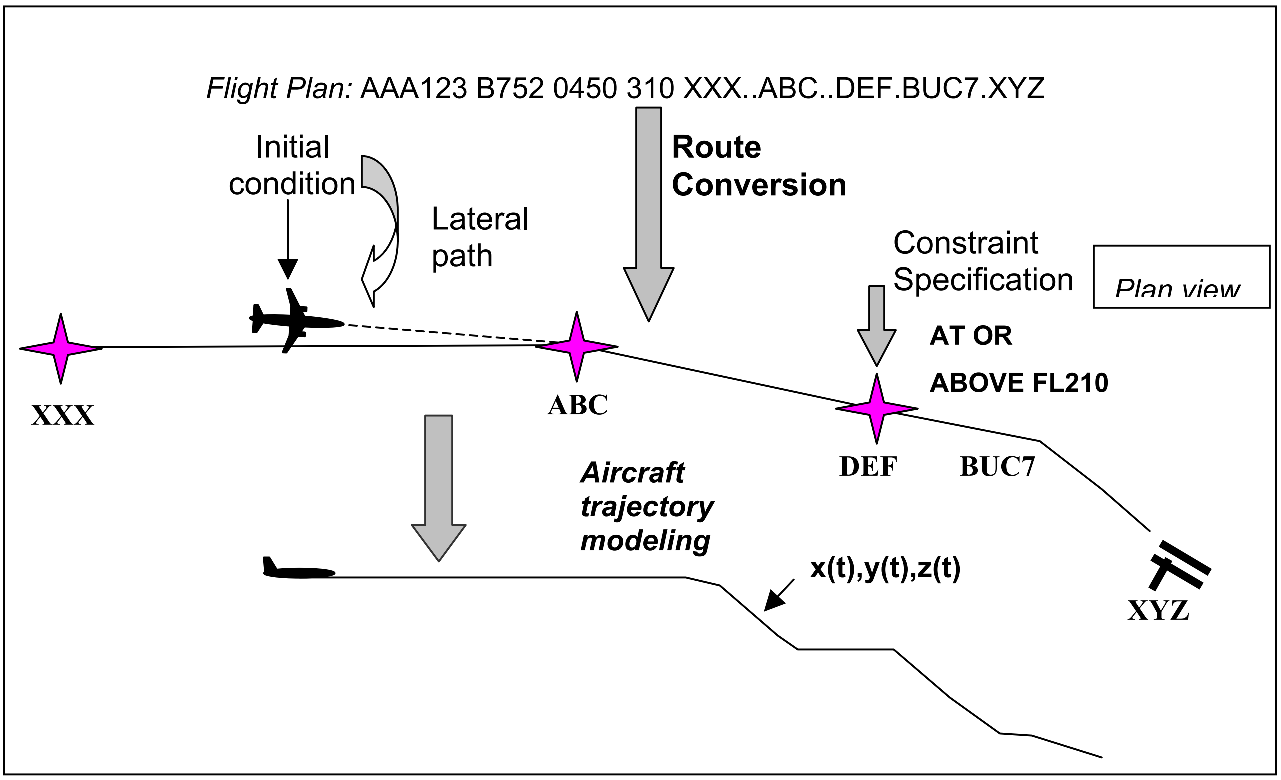

Figure 1: Aircraft Trajectory Prediction – Example in flight

Once the route is converted, a mechanism for joining the initial condition to the converted route is required. This process is referred to as ***lateral path initialization***. This process may simply involve the identification of the initial location on the route. At times the initial condition will be slightly off-route and some connection from the initial condition to the route will be required. A more generalized form of this trajectory service will be ***lateral intent modeling***, in which larger portions of the lateral path may be altered (e.g., depending on future traffic density forecasts).

Once the lateral path is determined, vertical and speed constraints must be considered at different points along the route of flight. This is the process of ***constraint specification***. For example, speed constraints below 10,000 feet can be applied, as can altitude constraints along a standard terminal arrival route.

The concept of ***longitudinal intent modeling***, while implicit in some trajectory predictors, refers to the addition of speed and altitude considerations to reflect how the combined controller, pilot and aircraft system will "fly" the aircraft. An example is the estimation of the top-of-descent, or the planned descent speed.

All of the above steps must be conducted prior to the calculation of a trajectory using any physics-based modeling. We refer to this collection of first steps as the ***preparation process***. The core part of aircraft trajectory prediction follows from the next step. In this part, the speed and vertical path is computed to follow the converted route, meet specified constraints (such as altitude and speed constraints), follow appropriate aircraft dynamics (such as turns, climbs and descents), and consider environmental and aircraft-specific information. The output of this process is that future positions of the aircraft are expressed as a function of time.

3.1. Trajectory Predictor Structure

The previously described trajectory prediction process is illustrated schematically in Figure 2. It illustrates the generic structure of a wide class of trajectory prediction software as applied to air traffic management DSTs (a major category of TP clients). The structure is meant to capture the salient features of many TPs. However depending on the nature of the TP client, some TPs incorporate only a subset of the services listed.

In addition to illustrating the preparation process described before, sources of data are shown. The output of the preparation process is the ***flight script***. The flight script provides the flight-specific information to a ***TP engine***. The TP-engine has access to aircraft performance data and meteorological data required to conduct trajectory prediction. The output of the trajectory predictor is a computed trajectory, which can be provided to a variety of TP export processes.

The ***trajectory update process*** is the process whereby the TP re-calculates its trajectory predictions. Trajectory predictors used by DSTs, other than in a trial-planning mode, tend to update the trajectory prediction based upon some trigger. This could be a time-based cycle (e.g., every x seconds), or based upon exceeding an error threshold in the last forecast. This update is in addition to the update required when input information has changed. Upon determination that an update is required, the trajectory update process will either launch a new preparation process or directly re-compute the flight script.

3.2. Trajectory Predictor Engine Types

Aircraft trajectory prediction can be accomplished using several different types of dynamical models within the TP engine. These engines may require different aircraft-specific and operational data to yield trajectory forecasts at different levels of precision. Generally, the various TP Engine types utilize different dynamic models:

- *A full six degree-of-freedom trajectory calculation.* This approach models the forces and moments (loads) affecting the airframe along all axes of motion as a function of the aircraft state and control settings. Accurate functional relationships between the loads and state/control values are typically obtained from the aircraft and engine manufacturers. These relationships can be expressed in tabular or fitted polynomial form as they are derived from measurements. Furthermore, since the aircraft is controlled through operation of control surfaces and engines, this model requires knowledge of the control laws for determining the control settings.
- *A point mass model (kinetic).* This approach models the aircraft as a point and only requires the modeling of the resulting longitudinal forces affecting this point – Thrust and Drag (it is

typically assumed that the lift compensates the weight). If required, fuel flow can be modeled as a function of Thrust. Thrust, drag and fuel flow data can be expressed in tabular or polynomial form. The reference data required to produce such a model needs to be thrust data (e.g. installed net thrust), drag data (e.g. for high/low speeds and for each a/c configuration) and thrust specific fuel consumption. However as this data is difficult to obtain, profile data (e.g. altitude vs. time) may be used. These data represent the motion of the aircraft as a result of the combination of all the forces affecting it ((thrust-drag)/weight). In order to differentiate individual forces from this set of integrated reference data, a large set of profile data must be used covering the whole flight envelope and the associated operating regime (e.g. climb thrust, idle, etc.).

- *A macroscopic model (kinematic).* This approach models the macroscopic behavior of the a/c (e.g. rate of climb/descent, rate of acceleration/deceleration) as a function of a set of input parameters affecting that behavior (e.g., altitude, temperature). The reference data required for the modeling process is limited to a/c rates of change and does not require the availability of thrust and drag data.

The above list of model types is ordered in accordance with level of fidelity of the model. However, the reader is cautioned that the trajectory prediction accuracy is a function of both the modeling and the quality of the input data used to drive the model. For example, a macroscopic model considering many operational conditions could produce better results than a 6-dof model using engineering approximations and standard conditions. Thus, data quality is an equally important factor in the ability of trajectory predictors to yield adequate results.

The form of the data used to drive the trajectory prediction models may also vary for each model. For example, aircraft performance data may be expressed as polynomials, look-up tables, analytical expressions or combinations of either. Each type of model may use data expressed in any of the above forms. Furthermore, the quality of the data is independent of the data's form.

3.3. Trajectory Predictor and Air Traffic Management Environment

We have described a TP structure applicable to a wide variety of DST applications and trajectory predictors that are in use or in development today. In this section, we discuss the broader environment in which a TP would operate, and the actual system that the TP seeks to model.

We borrow from [4] the control loops and command structure in today's air traffic management (ATM) environment, and introduce some modifications (see Figure 3). We have decomposed the decision aid to include a ground-based trajectory predictor (TP) as a front-end. This TP takes input from a variety of sources such as surveillance data, flight plan data, atmospheric forecasts and amendments to the flight plan data. Within the context of this ATM system, the role of the trajectory predictor is to provide the decision aid a forecast of the future flight path of the aircraft, given current available knowledge. Trajectory predictors accomplish this objective by applying a model of a portion of the system described in Figure 3 as the "typical TP modeling domain".

This typical TP modeling domain is shown as a dotted line in Figure 3. Many other TP constructs can be envisaged. For example, an airborne trajectory predictor can be developed that obtains information from onboard sensors and automation and modifies them for entry into the CDU (e.g., see [5]). However, for the purposes of describing a validation framework, this paper will focus on ground-based trajectory predictors. Furthermore, many trajectory predictors will also attempt to model a portion of the Air Traffic Control (ATC) block by modeling the "ATC intent". This model may be as straightforward as modeling the turn-back after an initial vector has been assigned.

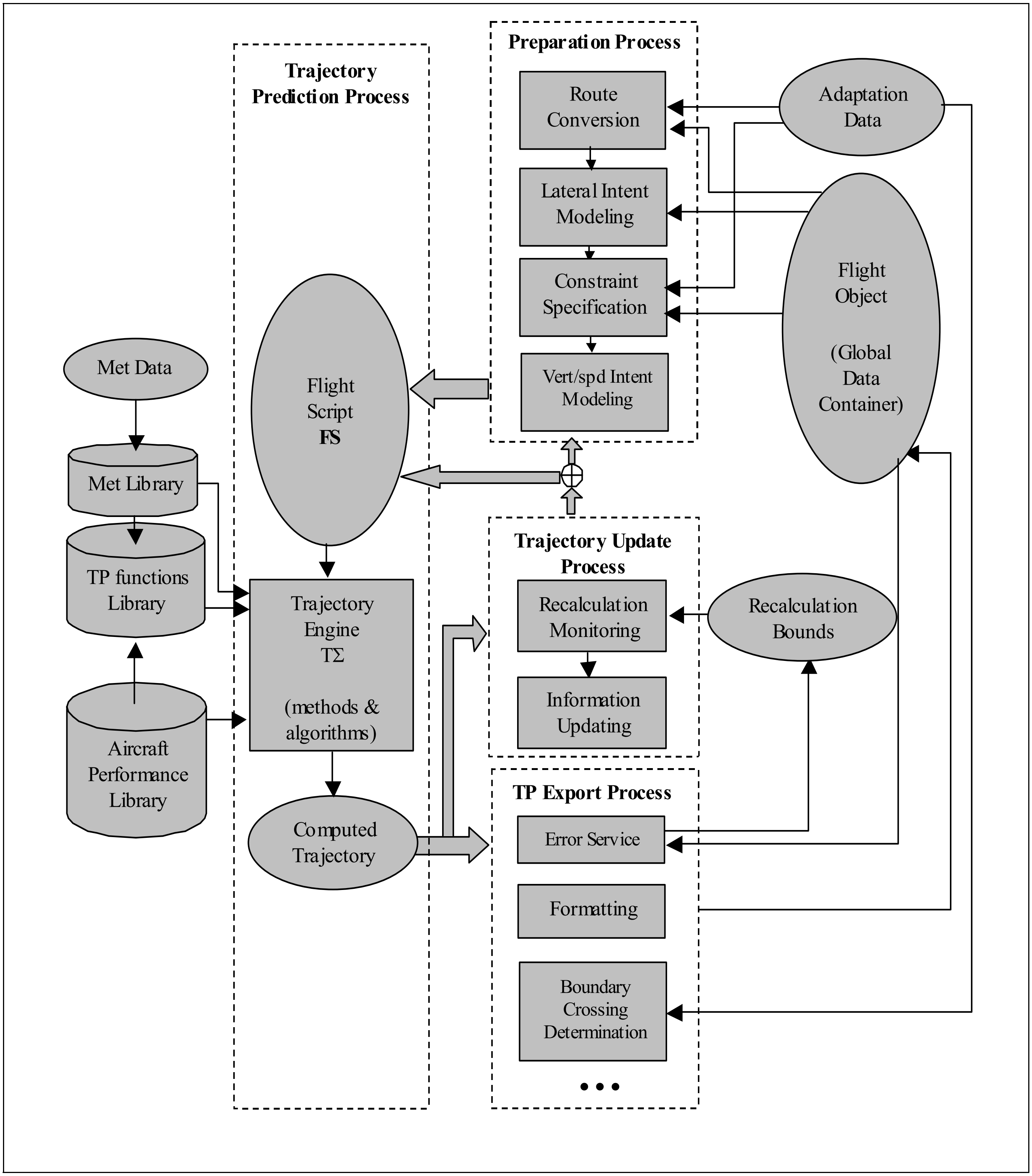

Figure 2: Schematic view of the TP structure (detailed description in [3])

By comparing Figure 2 to Figure 3, it is apparent that many TPs for DST applications model an abstraction of the physical processes and systems within the ATM environment. In addition to introducing modeling errors, this approach introduces validation challenges, as no simple one-to-one mapping exists between the physical systems and the TP model components. One can describe the TP modeling domain as a “black box” and validate input/output relationships. However, all modeling errors are combined and it becomes difficult to determine which errors need to be addressed to improve overall performance. In addition to modeling errors, other errors can affect the outcome of the TP.

Figure 3 also illustrates the impact of various exogenous errors. For example, errors in an atmospheric forecast (e.g., wind/temperature uncertainty) can perturb the actual aircraft trajectory from a forecast. Sensor errors can introduce errors in the validation data and introduce errors in the initial conditions used by a TP. For example, obtaining speed information from positional radar data results in poor error characteristics for the speed information [6].

One additional source of error is the ATC intent-type data will often be missing or in error. For example, flight path changes issued by voice are often not input into the automation [7].

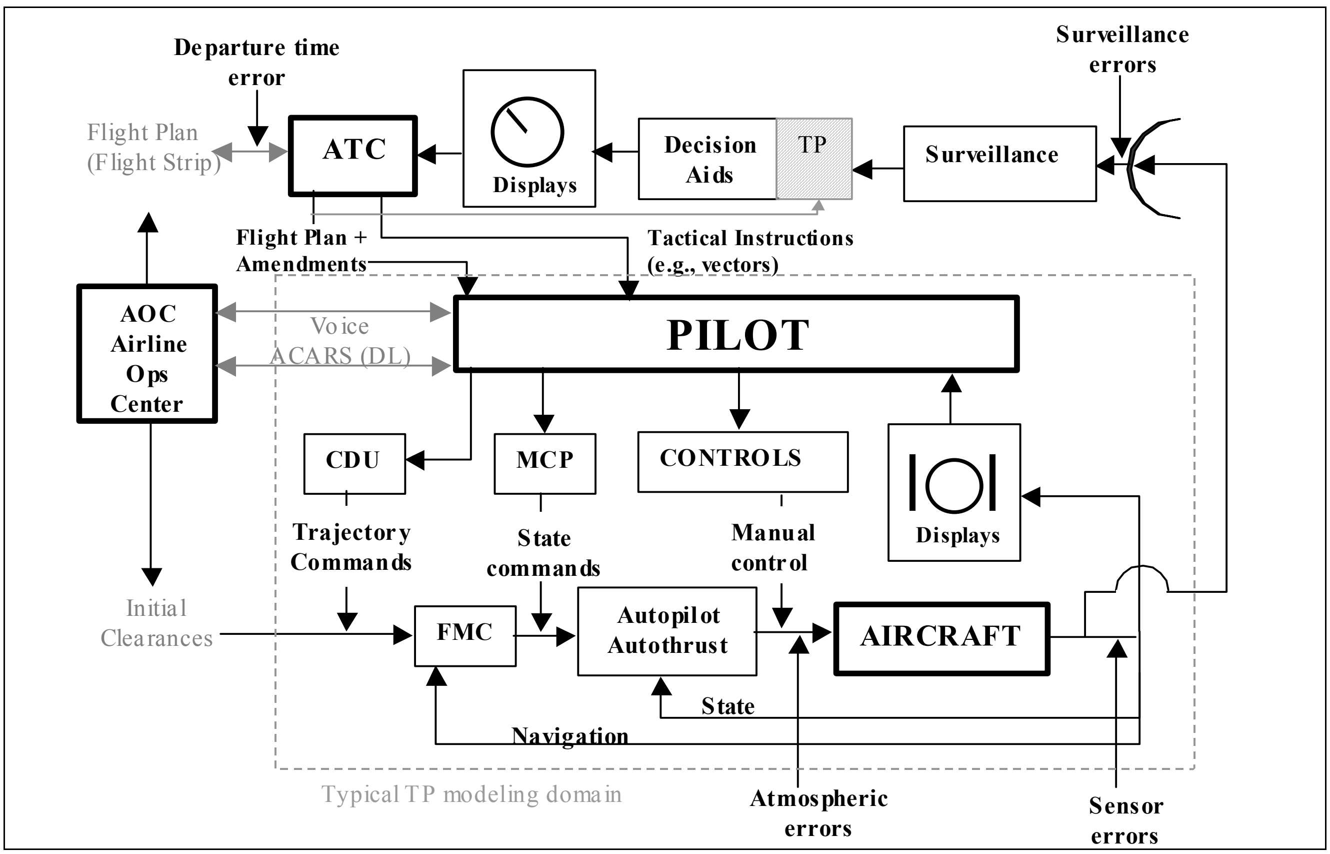

Figure 3: Control loops and command structure in the ATM environment (adapted from [4])

4. Trajectory Validation Data Types

Validation of trajectory predictors for DST applications relies on data that is available from a collection of sources. These sources can be categorized as follows:

Derived data – This data is obtained from more accurate and validated models of isolated portions of the system.

- Aircraft performance model data
- Flight simulator and Flight Management System (FMS) data

Traffic (Operational) data – This data can represent a more extensive set of flight conditions. Since this data is obtained from operations, the data will be less controlled than the derived data.

- Aircraft flight data recordings
- ATC operational data

Looking at each one of these data sources within the context of the ATM framework, we can understand which part of the ATM system is being measured. By understanding the relationship between the ATM structure and the TP structure, we can then understand which portions of the TP model can be validated using the different data types. By isolating the TP portions being validated, TP designers, and those responsible for future TP requirements, can understand the performance of various segments of the TP, and which need to be improved to achieve overall performance improvements.

4.1. Aircraft Performance Model Data

This type of data is generated from aircraft manufacturer-provided data. Only the vertical profile of the aircraft is modeled (often with a standard atmosphere and zero winds). Multiple profiles may be obtained as a function of weight and target speed. Figure 4 shows the portion of the ATM system being captured by this data. However, even this portion is only captured under a limited set of conditions.

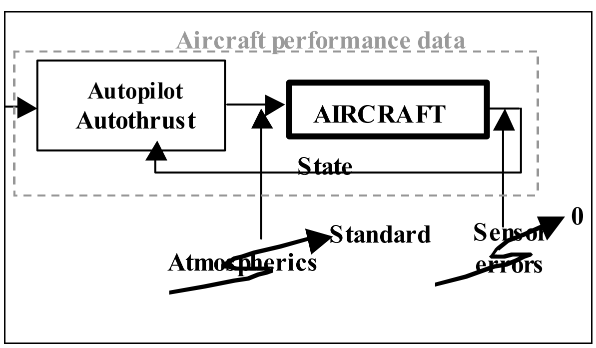

Figure 4: Aircraft Performance data portion of ATM system

For this type of data, both the lateral and longitudinal intent of the flight are known. The only portion of the system being stressed by application of this data is the vertical profile elements of the TP engine. Regardless of the type of TP engine being used, this data can be used to validate the vertical performance of the TP engine under controlled conditions. Libraries used by the TP engine to generate the vertical profile can also be validated.

It should be emphasized that by looking at input/output relationships under specific circumstances, one is only validating those relationships under the tested circumstances. For example, a point-mass model may be obtaining adequate trajectory profiles, but this does not imply that the aircraft thrust is modeled correctly.

4.2. Flight Simulator/FMS Data

This type of data may be obtained from human-in-the-loop flight simulators and from internal Flight Management System data. Beginning with the FMS data, the Flight Management Computer (FMC) contains an internal model of the aircraft trajectory and dynamics that is used to generate flight paths used for navigation. Figure 5 illustrates the portion of the ATM system being modeled in the FMS data. Since the data is simulated, sensor errors are not present (unless specifically introduced as an experimental control). Atmospheric data can be specified to the FMC and therefore a broader set of conditions can be investigated than with the prior data type.

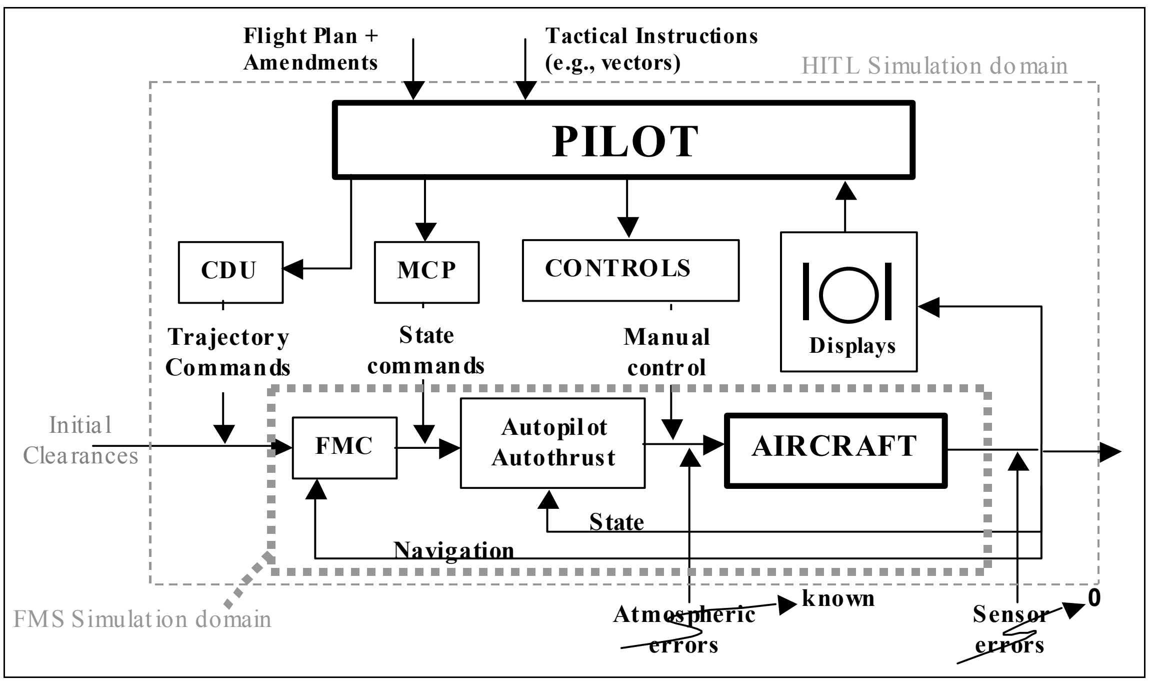

Figure 5: FMS and pilot-in-the-loop simulation data - portion of ATM system

By validating against FMS data, the vertical performance of the TP engine can continue to be validated under a broader range of controlled conditions (e.g., wider atmospheric conditions). Since constraints can be specified to the FMS, this type of data can be used to validate the *application* of constraints within the trajectory engine[2].

[2] This does not verify the specification of constraints during the preparation process, since the specification of constraints may require the determination of implicit constraints that are not necessarily known to the FMC. For example, standard operating procedures may require an altitude crossing constraint on all jets with a specific destination. A TP would have to first *specify* this constraint (e.g. cross XYZ at FL240), and then *apply* the constraint when building the vertical profile. In order to build a profile, the FMS assumes constraints have already been specified to.

One portion of the preparation process that can be verified using FMS data is route conversion since route conversion is conducted within the FMC (provided a unique mapping exists in the route definition of the ground and airborne systems).

Validation of the lateral performance of the trajectory predictor can be verified using FMS-simulated data. However, this verification is only applicable to flights for which the aircraft is following the FMS-based flight path. As soon as MCP or manual commands override the CDU command path from the pilot to the aircraft, this validation data is no longer fully applicable.

Pilot-in-the-loop simulations extend the domain further to incorporate almost the entire TP modeling domain (see Figure 5). Pilot intent is now incorporated into the data and the modeling of pilot intent can be validated. Within the TP structure, pilot intent is captured within the lateral intent modeling and vertical/speed intent modeling elements. Under normal operations, this broad term (pilot intent) captures certain pilot decisions such as the timing of certain actions (e.g. descent initiation, turn initiation), lags in response to commands and which modes to use (e.g., manual or heading select). If the simulation data includes the pilot inputs (into the CDU, MCP and manual controls) then the actual pilot intent model can be validated directly.

In addition to validating pilot intent, pilot-in-the-loop simulations can be used to validate the TP when the aircraft is operating under different types of pilot command paths and control modes. Ideally, the complete set of control modes would be available for each control path (e.g., FMS, MCP, manual).

4.3. Aircraft Flight Data Recordings

Aircraft flight data recordings are obtained from actual flight operations. The high cost of obtaining this information results in a data set that is limited to a small set of operational cases. When collecting aircraft flight data recording, the entire set of control loops is present as shown in Figure 3. Unlike human in the loop (HITL) simulation data, aircraft data recordings are subject to uncontrolled (albeit possibly measured) atmospheric disturbance and sensor noise. Also, depending on the breadth of data available, greater variation will be present within the data. Aircraft performance will likely vary within aircraft types, and pilot procedures will vary due to air carrier policies and pilot differences.

This type of data allows the same type of validation exercise as the prior data types subject to an operational environment. If a HITL simulation revealed a certain level of performance, validation through application of aircraft flight recordings would reveal its robustness. For example: whether the TP pilot intent model is valid across carriers; whether the aircraft performance is valid in the real-world across multiple airframes (of the same type); and how the aircraft and atmospheric models perform subject to real-world disturbances. As before, it is desirable to have a complete set of control modes and control paths.

Operational constraints will be applied to these flights and the communication of those constraints to the flight deck will be known. This data can contribute to the validation of the constraint specification portion of the preparation process (e.g., are the correct constraints being applied to the flight script?)

Given the operational nature of this data, the influence of controller intent will be present in the clearances that are provided to the flight deck. However, a fundamental difference exists between this data and the information that is often used by an operational TP. The flight data recording will include most if not all the instructions that are communicated to the flight crew. Real-time TP applications do not have access to this type of data. Thus, part of the TP controller intent modeling involves the inference of the current clearance (e.g., “is there a vector?”). A second portion of the controller intent modeling involves the inference of future events (e.g., where will the turn-back be?). By having access to the full controller intent, this data can be used to validate the performance of the TP once these instructions have been correctly placed into the flight script.

An analyst might be tempted to remove the instructions in order to validate the TP controller intent model. However, some specific knowledge of the TP is required to determine if this validation is appropriate. If the TP controller intent model relies on information from just the one flight being modeled, then this approach is legitimate. Yet, a TP may use additional information, through a DST, to determine the likelihood of a maneuver. For example, metering information, traffic information and other hazard information could all be used in a model of controller intent. In this situation, this data type could be applied in combination with ATC operational recordings to provide a validation of the controller intent model.

4.4. ATC Operational Data Recordings

This data type can provide more flights than available through other data types. The data elements include radar surveillance data, ATC clearance instructions, and atmospheric data. As for all operational data, the effects of the full control loops (see Figure 3) are observed in this data. One of the major distinctions between this type of data and the aircraft flight data recordings is the quality and availability of information available per flight.

ATC operational data is subject to significant surveillance errors, sometimes also including the filtering effects of the tracker. Detailed information about the flight is likely to be missing such as:

- Pilot intent (e.g., target speed)
- Mode information (e.g. MCP information)
- Aircraft parameters (e.g., aircraft weight)

The full controller intent may also not be known if voice recordings are not available. Thus the flight script may not be known for the flights being investigated. However this is not a hard rule. Since the quantity of this data is often high, filtering techniques can be employed to focus the analysis on portions of the flight where the flight script is more complete (e.g. see [8]).

While this data type is often limited in extent, in some cases this data closely represents that which is available to some current ground-based decision support tools [9]. For these types of tools, the data can be used to conduct validation of the complete TP under actual operating conditions. The results will provide performance characteristics of the TP under actual situations. If a validation exercise has been conducted on other aspects of the TP, and the overall performance characteristics of the TP are valid, then we *infer* that the TP ATC intent model is adequate. More direct evaluation of the ATC intent model may be conducted when voice data is available including all ATC instructions to the flight deck.

For other trajectory predictors requiring more information than is present in this data type, some additional data recording may result in supplementing the data with the requisite information. One must exercise care in supplementing the data through approximation, as validation of the controller intent model may no longer be appropriate. For example, if aircraft weight is required by a TP, but the data does not contain the weight. One could estimate the weight for the data set, but then one would be unable to differentiate between the effects of aircraft weight and some ATC intent effects (e.g., expedite climb).

5. Trajectory Accuracy Metrics

To perform an assessment and validate a trajectory model requires the measurement of the model's prediction positions, speed, and/or heading versus the corresponding true quantities that the aircraft actually travels. Thus, the goal of this measurement task is to ascertain the level of correctness and conversely the error in the trajectory prediction process with the ultimate objective of making improvements where the error is unacceptable. To achieve this, prescribed measurements are needed to capture the values of these errors, referred to as accuracy metrics. As described in [3], accuracy is "the degree of conformance between the estimated, measured or desired position and /or the velocity of a platform at a given time and its true position or velocity."

There are many aspects of trajectory accuracy measurement. Larger datasets as expected with the ATC Operational Data Recordings described in Section 4.4 may require sampling techniques as defined in [10] and filtering methods as in [8]. Inferential statistics are sometimes employed to prove or disprove hypotheses. The trajectory measurements themselves are often calculated as a function of the time horizon or look-ahead time at which the trajectory prediction is being made. Other factors are also considered such as the phase of flight or navigation equipage of the aircraft (see [11] for a list). For example, it is expected that the trajectory measurement errors would be higher during the climb as compared to level flight. However, the focus of this paper is to present the various definitions of the measurements themselves, foster discussion, collaboration, and eventually agreement on a set of accepted metrics that can be used to effectively compute a TP's trajectory prediction accuracy and compare them.

The following sections will define a set of generic accuracy metrics that quantifies the error in a trajectory model's predictions. The metrics are sub-divided into two main categories: Section 5.1 presents instantaneous positional errors and Section 5.2 presents speed and heading errors.

5.1. Instantaneous Positional Errors

As defined in [3], the instantaneous trajectory prediction error is the measured difference between the actual aircraft position at a particular time and the forecast position along a predicted trajectory at the same time. There are two broad categories of measurement for this positional error. First, there are spatial errors that are concerned with measuring the different between the aircraft's actual and predicted position in space. Next, there are time errors that are also measures between the aircraft's actual and predicted position but in terms of time.

5.1.1. Spatial Errors

The spatial errors are defined by dimension.

5.1.1.1. Horizontal Error

As first presented in [10], the horizontal error of a trajectory prediction is the straight-line difference in the horizontal plane between the actual position of the aircraft and the time coincident trajectory predicted position (distance between P1 to P2 in Figure 6). There is little ambiguity in the calculation of horizontal error, since it is always the unsigned distance between the same two time-coincident points, namely the actual position and predicted position. If the trajectory and actual position of the aircraft is projected on to a stereographic plane, the horizontal error is literally calculated as a straight-line in the stereographic flat plane. If the trajectory and actual positions are provided in spherical coordinates, the horizontal error is calculated as the great circle arc between the same two points. Since the horizontal error is a relative difference, any discrepancies between the stereographic and spherical versions are expected to be quite small. This is different than the following two metrics, since there are multiple versions depending on the selection of predicted position.

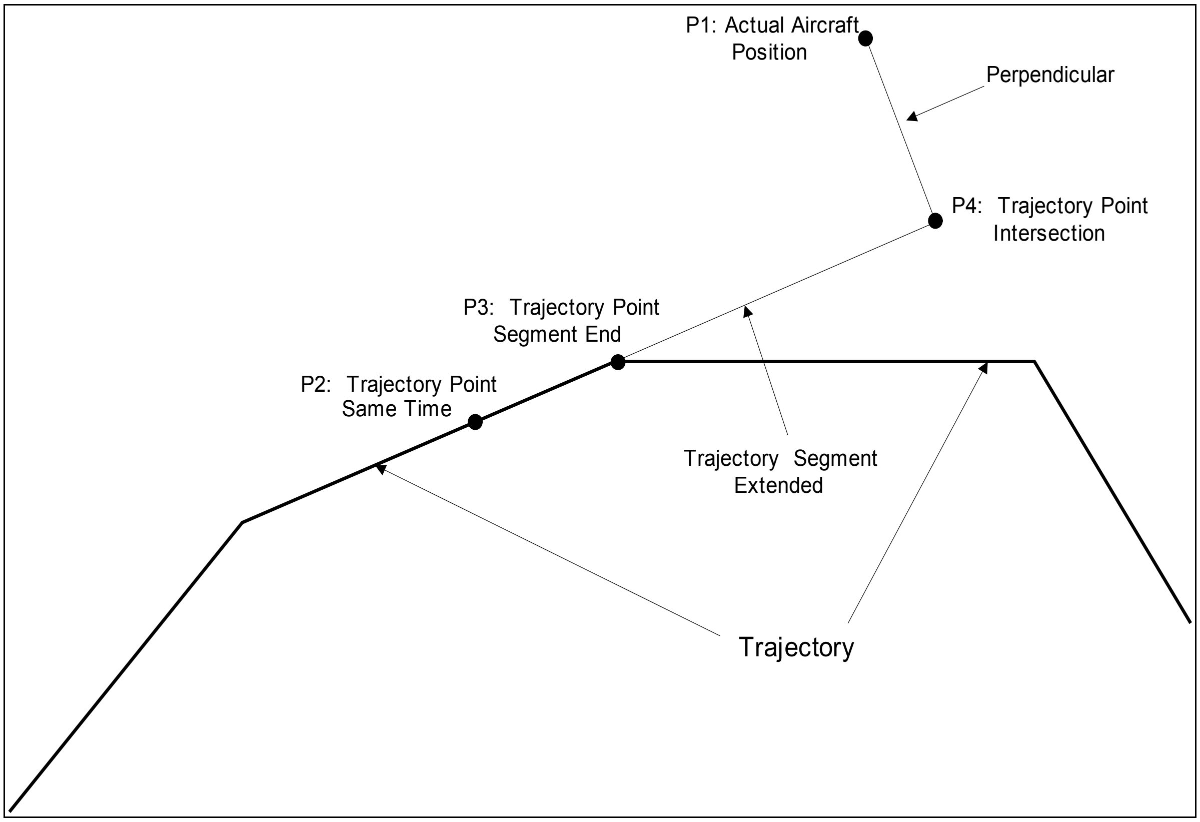

Figure 6: Time Coincident Accuracy Metrics

Presented next are the two approximately orthogonal components to the horizontal error: the longitudinal and lateral error.

5.1.1.2. Time Coincident Longitudinal and Lateral Errors

The longitudinal or along track error represents the component of the instantaneous trajectory prediction error that is parallel to the along trajectory ground path. The lateral error represents the side-to-side, or cross track, difference between the actual and its corresponding trajectory prediction point. As illustrated in Figure 6, the exactly orthogonal components to the horizontal error are formed by the line extension of the time coincident trajectory point P2 to the end point P4 of the perpendicular from actual aircraft point P1. The distance from P1 to P4 is the lateral error, while the distance from P2 to P4 is the longitudinal error. The lateral error is positive if to the actual position is to the right of the trajectory and negative otherwise. The longitudinal error is positive if the actual aircraft is ahead of the time coincident trajectory point and negative if behind.

5.1.1.3. Spatially Coincident Longitudinal and Lateral Errors

Depending on the needs of the analyst, there are two acceptable versions of the spatial metrics of longitudinal and lateral errors. As defined previously in Section 5.1.1.2, the longitudinal and lateral errors can be calculated as exact orthogonal components of the time coincident horizontal error. In this section, the perpendicular end point P4 is calculated by projecting onto the nearest trajectory segment not the line extension formed by the time coincident trajectory point. This is illustrated in Figure 7 where the perpendicular distance from P1 to P4 is again the lateral error but represents the closest distance from the actual aircraft position and trajectory. The longitudinal error is the distance along the trajectory from point P2 to P4 (i.e. the sum of the two trajectory segments of P2 to P3 and P3 to P4). Therefore, the point P4 is assumed the spatially coincident point between the actual and predicted position on the trajectory. It is not really spatially coincident but assumed so, since the prediction point P4 is the closest predicted position to the actual aircraft. The sign conventions are the same as defined in Section 5.1.1.2 metrics.

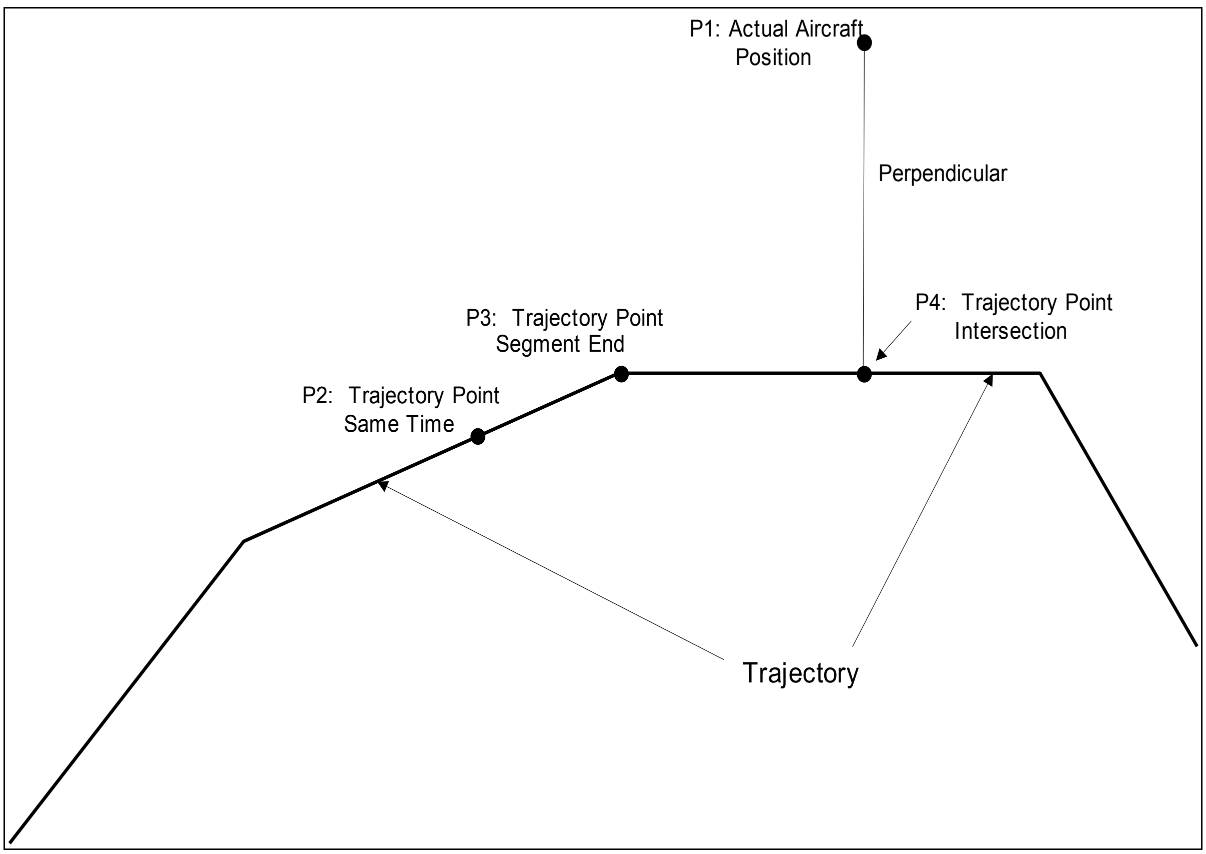

Figure 7: Spatially Coincident Accuracy Metrics

This spatially coincident version of the longitudinal and lateral errors requires additional design considerations during the predicted turns of the aircraft. There are two variants to processing these errors when the P4 cannot be projected precisely on the trajectory.

5.1.1.3.1. Turns Assumed Instantaneous

When an aircraft is near a predicted turn, it is possible that the perpendicular in Figure 7 from P1 to the trajectory results in a point P4 that is not on the nearest trajectory segment but on an extension of this segment. This is illustrated in Figure 8. If this occurs, the distance from P1 to the nearest trajectory end point is used as the lateral error instead of the perpendicular distance. Therefore, in the example in Figure 8, the lateral error is the distance from the trajectory endpoint P3 to the actual aircraft position P1. This occurs only when the trajectory intersection point P4 is projected off all trajectory segments during a turn.

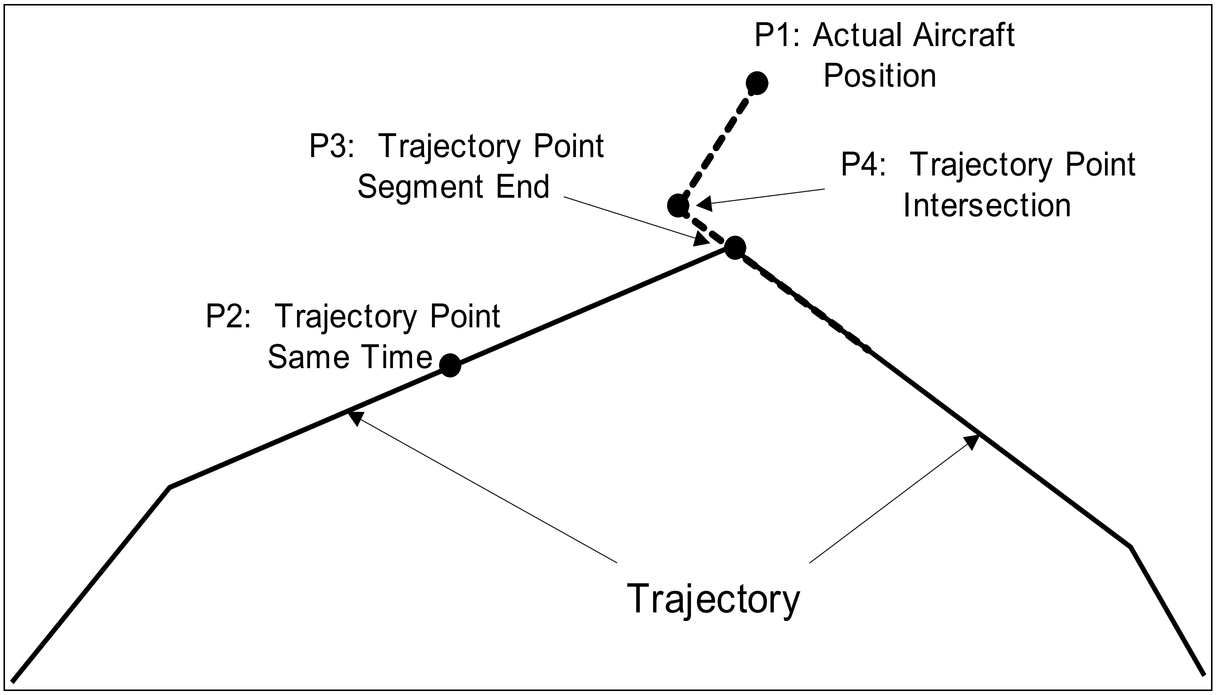

Figure 8: Error During Instantaneously Modeled Turn

5.1.1.3.2. Turns Assumed at Adapted Constant Turn Rate

Aircraft do not turn instantaneously, but turn along a curve based on the pilot's discretion and navigational performance of the particular aircraft. Turns can also be predicted more precisely by modeling the turns closer to what they actually fly. As presented first in [12] and applied in [13] if an analyst is evaluating such a trajectory, Figure 9 illustrates a variant of the spatially coincident lateral and longitudinal errors by modeling a turn with a constant circular arc. The position P5 is the center of this constant radius turn. If the actual aircraft position falls within the wedge formed by P5 to P3 and beyond and P5 to P6 and beyond, then the lateral error is calculated from the line segment from P1 to P4, where P4 is the intersection on the arc and along the line segment from P1 to P5. The longitudinal distance is calculated similar as before now along the arc from P4 to P3 plus the straight trajectory segment like before from P3 to P2.

5.1.1.4. Vertical Error

The vertical error is the difference between the time coincident actual aircraft altitude and predicted trajectory altitude position. There is no ambiguity like the horizontal error presented in Section 5.1.1.1, but unlike the horizontal error, the vertical error is signed. If the actual aircraft is at an altitude above the trajectory predicted altitude, the vertical error is positive and negative if the aircraft is below the prediction.

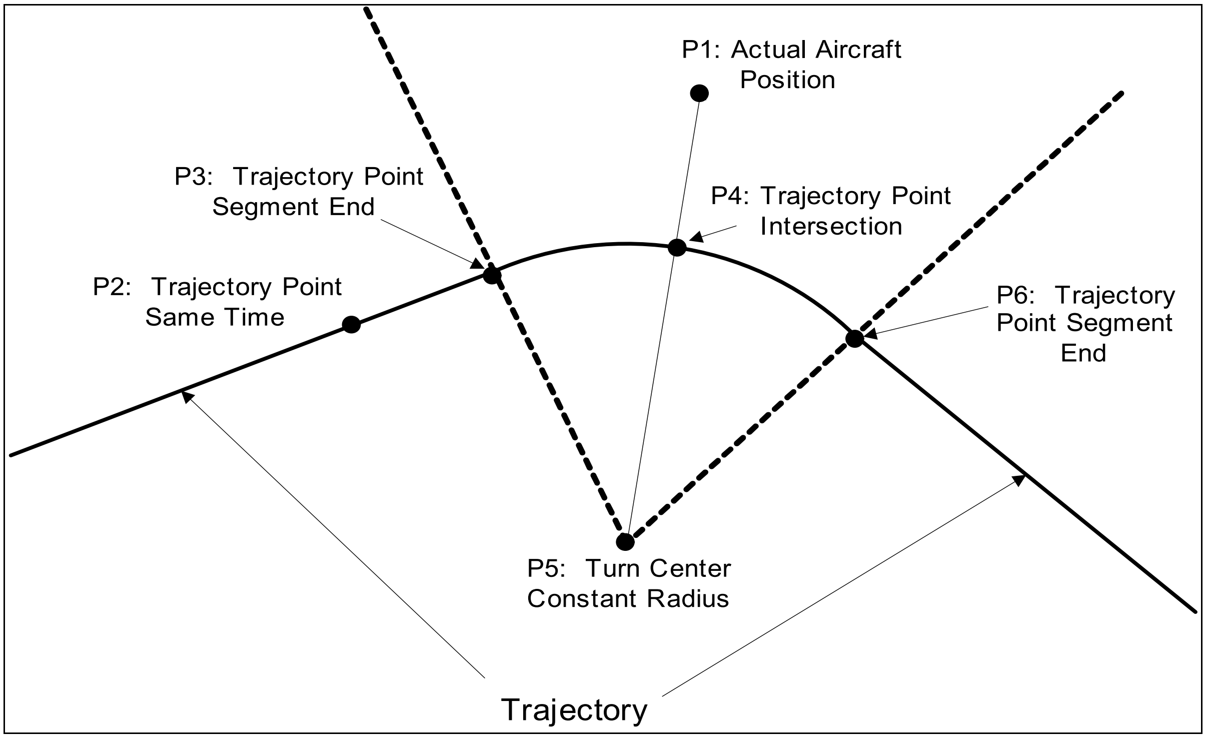

Figure 9: Error During Constant Circular Arc Modeled Turn

5.1.2. Time Error

Time error is the deviation in time between spatially coincident track and predicted trajectory positions. These errors are similar to the longitudinal error defined in the spatially coincident errors in Section 5.1.1.3, but as illustrated in Figure 7 the time error is the difference in time from the trajectory point P2 to the projected trajectory point P4. Similarly, the same methods applied in Sections 5.1.1.3.1 and 5.1.1.3.2 are applied for the time error. Like the longitudinal error, positive time error indicates the actual aircraft position is ahead of the trajectory predicted position and negative is behind. For example, if the aircraft intercepts a trajectory position sooner than predicted, the time error is positive.

5.2. Speed and Heading Errors

Speed errors are computed by the differences between the actual ground, air, and wind speed and the corresponding time-coincident predicted speeds. The heading, course, and wind direction errors are measured in terms of actual versus predicted as well but require conventions in terms of range of values and directions. The following list of definitions further explain these errors:

1. **True airspeed error** is computed as the difference in magnitude between the actual and predicted true airspeed of the aircraft.
2. **Ground speed error** is computed as the difference in magnitude between the actual and predicted ground speed of the aircraft.

3. **Wind speed error** is computed as the difference magnitude between the actual and predicted wind speeds. Wind speed can be calculated at any point in space (e.g. National Weather Service Rapid Update Cycle grid point) or from the aircraft location.
4. **Heading error** is the difference in degrees of the aircraft's actual true heading (consistent with the aircraft's Directional Gyro and with respect to the air) and predicted.
5. **Course error** is the difference in degrees between the aircraft's actual and predicted course angle (i.e., aligned with the physical path/route in space relative to the ground).
6. **Wind direction error** is also the difference in degrees between the aircraft's actual and predicted wind direction. Although unlike the course and heading angles, the wind direction is the angle in which the wind is coming from.

The angles presented above (e.g. heading, course) are between 0 and 360 degrees, that is [0, 360). Heading, course and wind direction errors are by convention +/- some angle less than 180 degrees. The sign convention is "+" for clockwise and "-" for counterclockwise[3].

[3] The convention is intuitive and fairly trivial, yet critical to the definition of these metrics. Therefore, a set of algorithms is presented in the Appendix (see Section 8) that illustrates the details and eliminates any ambiguity.

6. Recommendations for Community Participation

As presented in the previous sections, a framework for a TP validation strategy has been proposed to promote the advancement of trajectory predictor performance. The strategy requires incorporation of specific validation methodologies and the construction of a sizeable database of validation trajectory data as described in Section 4. We encourage your participation in the following ways (summarized in Figure 10):

1. **Provide feedback on this validation data methodology white paper.** To meet the Action Plan 16 objective of developing a comprehensive validation database and TP validation strategy that is effective, efficient, and accepted by all, absolutely requires community input. We encourage you to provide comments on the topics presented in this paper. All your comments will be reviewed thoroughly by the team and incorporated in a subsequent version of the paper. Please use the attached comment form (file name: "ActionPlan16Comments01.doc") and mail to: tim-tp@cena.fr by October 25, 2004.
2. **Participate in the upcoming Technical Interchange Meeting[4] (TIM) organized to exchange community feedback on the validation methodology, organization of the database, and establish a list of continuing participants.** The TIM will promote open exchanges and discussions of validation approaches, allow the community to present internal successes of overlapping activities, and better explain the team's expectations of the effort. We encourage your participation not only by attending but also by presenting a briefing of your local validation methodology experiences. Please send a message with your intentions on attending and your proposition to tim-tp@cena.fr by October 1, 2004.
3. **Share specific TP validation methodologies and experiences.** Your experience is important, even essential, to the process. We encourage your feedback either through participation in the TIM discussed previously or correspondence directly with team members of Action Plan 16. The feedback you provide will ensure the effort continues to improve, making the data more accessible, readable, and most importantly useful. We encourage you to contact us directly as well. The two leads for Action Plan 16 include:
   - Sipke Swierstra (Eurocontrol), Sipke.Swierstra@eurocontrol.int
   - Steven Green (NASA), Steven.M.Green@nasa.gov
4. **Contribute your locally adapted validation reference datasets**. By providing your own examples of this data as described in Section 4, the community will be best served with a broad database of reference validation data. At the same time as your data is downloaded into the database, you may upload other sources of the various trajectory data. At present, this effort is still under construction with only preliminary samples of the various data types, but we encourage you to start planning what local datasets could be provided in the future, what format you would propose, and other access issues or concerns you may have. Please bring this information to the TIM discussed in (2) above and/or contact us directly as encouraged in (3) above. For access to Eurocontrol's OneSky Internet file server, where the validation data will eventually reside and where the preliminary data sets currently reside, register at:

[4] The TIM is scheduled for late November 30 through December 2, 2004. The logistical details will be provided in a separate document.

http://www.eurocontrol.int/oneskyteams.html under the OneSky Team's "Common trajectory prediction initiative."

5. **Utilize the validation database by uploading one or more of the data types and performing a validation exercise**. Ultimately the true value of the effort is the application of the TP validation strategy and validation data database by the participating service providers and TP developers. Although this is several months from fruition, discussed previously in (2), we encourage you to start planning how you would integrate the validation database in your local validation activities.

A common TP validation strategy requires community support to be successful, but most importantly it will serve the TP development community and the service providers and in turn the public. It promotes the advancement of TP accuracy and capabilities required for the implementation of DSTs and other tools that will improve system safety and efficiency of the ATM system.

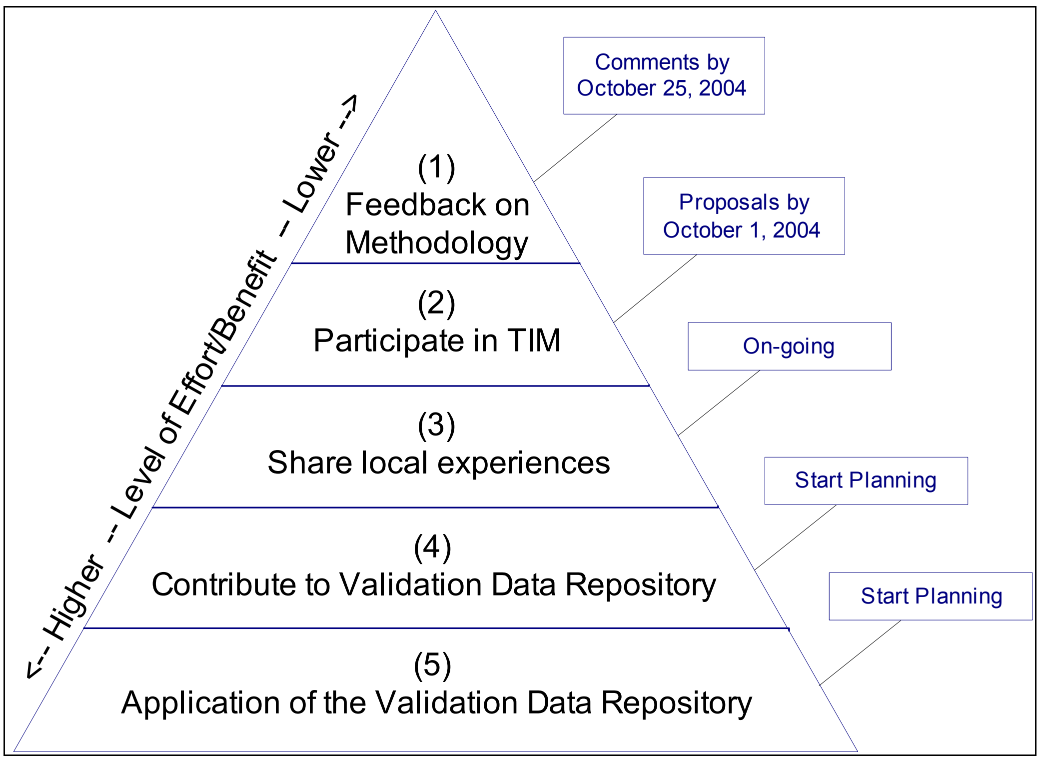

Figure 10: Summary of Recommendations for Community Participation

7. References

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[12] Green, Steven M. (October 2002) “Calculation of Trajectory Errors at Turn and Meter Fixes,” Technical Notes, NASA Ames Research Center.

[13] Williams, David H., Steven M. Green (July 1998) “Flight Evaluation of Center-TRACON Automation System Trajectory Prediction Process,” NASA/TP-1998-208439.

8. Appendix

The computation of taking the difference of two angles is trivial mathematically, but the applied convention is critical for defining heading and course error metrics. The following listing provides two options for subtracting one angle from another. The input angles are defined between 0 and 360 degrees, that is [0, 360). "**A**" represents the actual angle and a "**P**" represents the predicted. "**D**" represents the relative difference of "**P**" with respect to "**A**". The difference "**D**" is by convention less than +/-180 degrees. The sign convention is "+" for clockwise (i.e., "**P**" is clockwise relative to "**A**") or "-" for counterclockwise (i.e., "**P**" is counterclockwise relative to "**A**").

8.1. Pseudo Code for Option 1

```
D = P - A
if ( |D| > 180.0 ) {
 D' = 360.0 - |D|
 if D > 0.0
  D= -D'
 else
  D = D'
 }
}
```

8.2. Pseudo Code for Option 2

```
If ( P > 180.0 ) {
 P' = P - 360
else
 P' = P
}
If ( A > 180.0 ) {
 A' = A - 360
else
 A' = A
}
D = P' - A'
```